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SHG-based Technique for Examining Laser Diode Wavelength Dynamics in the μ s to ms Range

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Wavelength information is essential for any researcher in optics and photonics, and for this reason a wide range of devices are available for measuring it. However, the techniques available today are either limited to a resolution of nanometers or a measurement rate of kHz. In this paper we present a simple but highly versatile technique based on second harmonic generation to measure fast wavelength dynamics of laser diodes. We demonstrate a resolution of 0.7 pm and a measurement rate in the MHz range. The measurement rate is only limited by the photodetector and the wavelength resolution is mainly limited by the length of the non-linear crystal and the noise of the detectors. The technique can for example be used to investigate the mode hop behavior of laser diodes during pulsed operation. To demonstrate this, we show the wavelength changes of a laser diode during a single pulse.

OCIS codes: (140.3295) Laser beam characterization; (140.2020) Diode lasers; (190.2620) Harmonic generation and mixing

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1. INTRODUCTION

The wavelength is one of the most fundamental properties of light and its measurement is, therefore, essential to researchers in optics and photonics. For this reason there are many techniques for measuring wavelength, some of which are broadly used in commercial devices. For example, Optical Spectrum Analyzers (OSAs) based on scanning Michelson interferometers[1] yield a lot of information due to the generation of full spectra with a resolution down to roughly 10 pm. However, their measurement speed is also typically limited to a few Hz or slower and they require the spectrum to remain constant throughout a measurement. Grating based spectrometers can achieve significantly higher speeds by using line cameras, however, their spectral resolution is typically limited to about one nanometer by the grating. Streak cameras can push the temporal resolution to the radio frequency regime but they still rely on gratings for the spectral resolution. The spectral resolution can be pushed to a few pm using a double echelle monochromator while maintaining a measurement rate close to 1 kHz[2].

For single frequency lasers, wavemeters can push the spectral resolution down to femtometers by either speckle based methods[3, 4], or interferometry. However, these techniques still require either an array detector or a scanning mechanism and they are therefore still limited to kHz measurement rates.

Non-linear optics, and specifically second harmonic generation (SHG), has been utilized for decades to characterize ultrashort optical pulses with autocorrelation and frequency resolved optical gating

(FROG)[5]. For these setups a thin non-linear crystal is used to ensure that phase-matching is achieved for the entire spectral content of the pulse. In a special variation of FROG, a thick non-linear crystal is used with a tightly focused beam to map the angular dependence of the phase-matching onto a camera to eliminate the spectrometer usually used for FROG[6]. Due to the need for a wide spectral acceptance, these methods typically make use of birefringent phase matching. For lower peak power lasers, the efficiency of birefringent crystals is often too low to get sufficient signal. The above methods are, therefore, mainly appropriate for ultrashort pulses with high peak power.

Most systems can be sufficiently characterized with either a high wavelength resolution or a fast measurement rate. However, with the increased availability of frequency stabilized high power laser diodes has come an interest in the wavelength stability of these during arbitrary modulation. An example of this is modulation of the second harmonic light generated by frequency doubling of these laser diodes[7, 8]. Here the wavelength needs to be stable within a few tens of picometers during a single pulse. To the best of our knowledge there are currently no commercial systems capable of measuring this.

In this paper, we present a technique to determine wavelength dynamics of single frequency laser diodes, which utilizes the steep wavelength dependence of thick non-linear crystals. While the technique works with most types of non-linear crystals, we chose to use periodically poled materials since these enable tailoring the center wavelength to the desired spectral area and provide high conversion efficiency even for CW lasers. The center of the wavelength acceptance curve can be tuned with temperature, while the crystal length

determines the width of the curve[9]. By measuring the conversion efficiency of the crystal and comparing it with the crystals wavelength acceptance curve, the wavelength of the fundamental light can be deduced. Using this technique, we achieve sub-picometer resolution with MHz measurement rate and show the evolution of a laser diode's wavelength during a single pulse.

2. SETUP AND RESULTS

A sketch of the experimental demonstration setup is shown in Fig. 1.

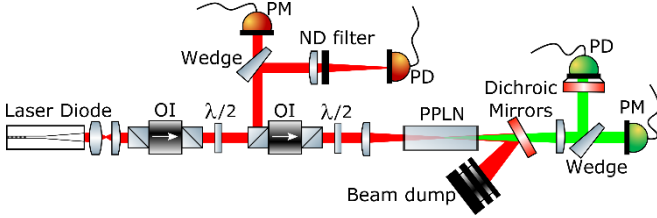


Fig. 1. Sketch of the demonstration setup. OI: optical isolator, $\lambda/2$: half wave plate, PM: power meter, PD: photodiode, ND: neutral density, PPLN: periodically poled lithium niobate crystal.

The laser used for the demonstration was a Distributed Bragg Reflector (DBR) tapered laser diode similar to the one described in[10]. The laser diode was protected from optical feedback by an optical isolator, after which a portion of the power was picked out using the first polarizing beam splitter of a second isolator. The pick-off light was split between a calibrated power meter and a fast photodetector (Thorlabs DET210) to allow for both calibrated measurements of the input power to the crystal and fast measurements of the input power by connecting the photodiode to an oscilloscope (Lecroy WaveSurfer 104MXs-A 1 GHz). The rest of the fundamental light was sent through the isolator to further protect the laser diode from feedback from the crystal and a half wave plate to align the output polarization to the phase-matched crystallographic axis. After the PPLN crystal the remaining fundamental light was separated before the second harmonic was collimated and split onto another photodiode (Thorlabs PDA100A-EC) and another calibrated power meter.

The non-linear efficiency η of the crystal is related to the fundamental power P_ω and the second harmonic power $P_{2\omega}$ through the following relation[11]:

$$P_{2\omega} = \eta P_\omega^2 \quad (1)$$

In this definition, η is independent of the fundamental power and is often given in units of %/W. It should be noted that this expression assumes negligible depletion of the fundamental power. However, for depletions below 5% this expression is a very good approximation. High powers can also lead to thermal effects in PPLN, which can affect the wavelength acceptance curve of the crystal and it is, therefore, important to stay at medium to low input powers (< 2 W) for these measurements. η is only calculated for points where the fundamental powers are significantly higher than the background noise.

The acceptance curve of an 8 mm and a 20 mm PPLN crystal was measured by varying the temperature of the laser diode and measuring the wavelength with an optical spectrum analyzer (Advantest Q8347) and the powers with the power meters. The crystal lengths were chosen to match the wavelength range of the dynamics seen in the tapered laser diode. The following formula was used for fitting:

$$\eta = a \operatorname{sinc}^2(\Delta\lambda/b) \quad (2)$$

The results are shown in Fig. 2. The fit was limited to an interval where there is a one-to-one correspondence between η and the

wavelength. η values outside this range are ignored. The one-to-one correspondence is only strictly valid if the instantaneous frequency is single frequency. The best fit parameters were $a = 0.805$ %/W and $b = 307$ pm for the 8 mm crystal, and $a = 2.09$ %/W and $b = 137$ pm for the 20 mm crystal.

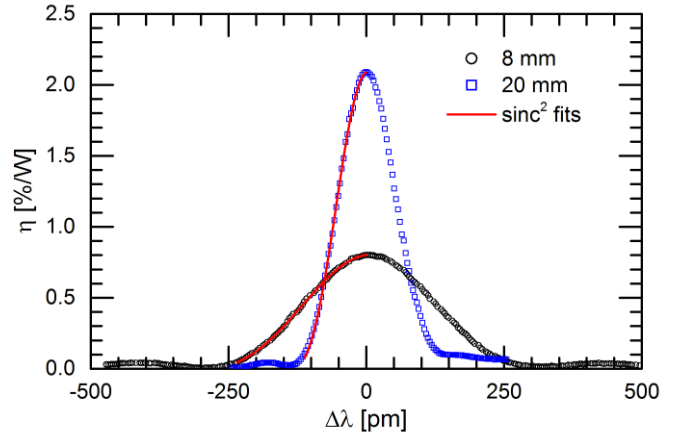


Fig. 2. Wavelength acceptance curve of an 8 mm and a 20 mm PPLN crystal. Fits to sinc^2 functions are shown in red. The fit is subsequently used to convert from η to wavelength.

It is important to ensure that the measurement is done on the correct flank of the wavelength acceptance curve. For our experiments this was done by operating the laser diode in CW (or quasi CW) and adjusting the temperature of the crystal to the half way point on the left flank. When a value of η has been calculated the sinc^2 fit is used to convert it to a wavelength offset from the peak of the acceptance curve. The absolute wavelength can then be found by adding the center wavelength of the acceptance curve. This center wavelength increases approximately linearly with the temperature of the crystal at a rate of 82.1 pm and 80.3 pm per kelvin for the 8 and 20 mm crystals respectively. Since the acceptance curve is defined by the material the calibration only needs to be done once, as long as the beam path through the crystal remains the same. For this work the calibration was done once for each crystal and no recalibration was needed over a period of a few weeks. For a free space setup like this, one could be concerned about shifts due to variations in the beam quality (M^2) and beam pointing. However, we did not find any significant influence of these parameters for the laser used in these experiments. The issue can also be avoided completely by using a fiber-coupled input, more rigidly defining the beam path and beam quality inside the crystal. For this paper we have assumed the laser is single frequency at all times. In many cases "multi-frequency" lasers are actually instantaneously single-frequency but experience rapid hopping between competing modes. In this case the technique is still valid if the hopping can be temporally resolved by the photodiodes and the possible modes are all within the measurement range. If, on the other hand, the laser has a number of closely spaced modes which coexist and are distributed within a range that is significantly narrower than the measurement range, then the interpretation of the results become more complex due to the fact that η depends on the number of modes and their distribution. If the modes are uncorrelated in phase, have equal power and the spectral distribution is infinitesimal compared to the acceptance bandwidth of the crystal then the maximum obtainable η scales as[12]:

$$\eta_{MM} = \eta_{SM}(2 - 1/N) \quad (3)$$

where η_{MM} and η_{SM} are the non-linear efficiency in multi-mode and single-mode operation for the same fundamental power and N is the number of modes. The technique presented here can, therefore, still be used for a multimode laser in this case if the number of modes in the laser remain constant but it would require a calibration for the specific laser. In principle the technique could also be used for a laser with a wider spectral distribution[13], but it would again require a calibration for the specific laser. The technique might also work in other special cases, however, in all cases it would require the multi-mode behavior to be constant to keep a correlation between η and the wavelength during the measurement and calibration.

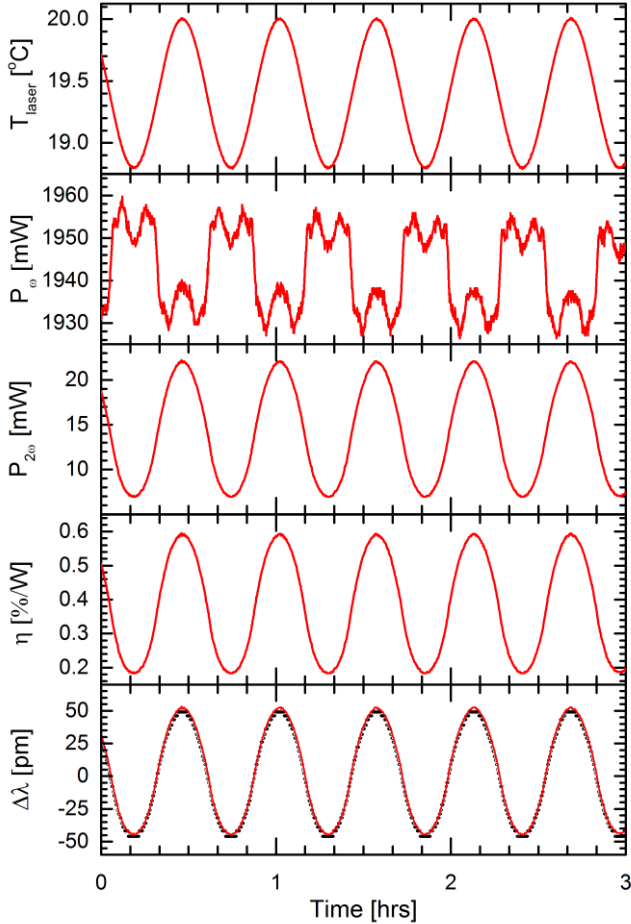


Fig. 3. Test (i), part 1. From top to bottom: Laser heat sink temperature (T_{laser}), Fundamental power input to the 8 mm PPLN crystal (P_0), generated second harmonic power (P_{20}), calculated non-linear efficiency (η) and a comparison of the wavelength ($\Delta\lambda$) measured by the OSA (black dots) and the SHG technique (red line). The center wavelength is 1061.7 nm. The bottom graph shows good agreement between the measurements.

In the first test (i) the temperature of the laser diode heat sink was varied as a slow sine function while simultaneously measuring the fundamental power, second harmonic power and laser temperature as well as the wavelength measured by the optical spectrum analyzer. Fig.3 shows the diode heat sink temperature together with the fundamental power, second harmonic power, the calculated non-linear efficiency (η) and both the calculated and measured wavelength. The fundamental power only varies by <2% and for this reason the calculated η closely follows the second harmonic power indicating that the temperature mainly influences the laser wavelength as expected. The maximum depletion is 1% so the low depletion approximation is

valid. Over a three hour period the OSA measurement and the calculated wavelength show very good agreement except for a small wavelength offset of 2 pm. This offset is likely due to the crystal temperature not being completely decoupled from the room temperature. When measurements from several days were compared this offset could vary a few tens of pm, but this problem can be overcome by better thermal management. This simple implementation of the SHG technique achieved a resolution of 0.7 pm with an 8 mm crystal and a thermal power meter.

Fig. 4 shows another 3 hour measurement using the 20 mm crystal while a slow sine function offset was applied to one of the injection currents to the laser diode. The conversion efficiency used with this crystal is 3%, so the low depletion approximation still holds. For this measurement a resolution of approximately 0.4 pm was achieved. From Fig. 4 it is clear that the resolution of our technique is a significant improvement over the OSA resolution of 3 pm. The resolution can be further improved by using a lower noise photodetector and/or using a longer crystal. A longer crystal will, however, decrease the measurable wavelength range for any fixed crystal temperature.

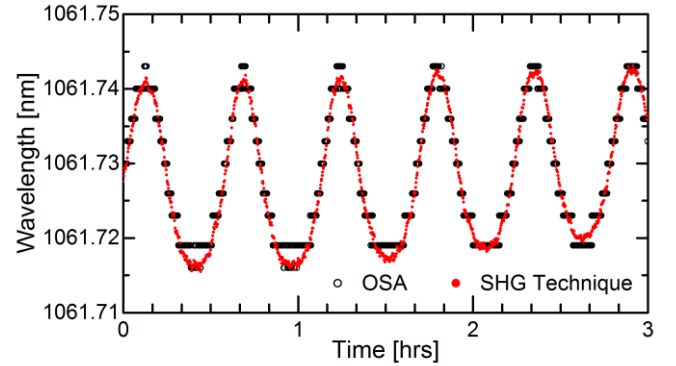


Fig. 4. Test (i), part 2. Wavelength of the laser diode measured with the OSA (black open dots) and the SHG technique (red closed dots). Our SHG technique shows approximately a factor of 10 improvement in resolution over the OSA.

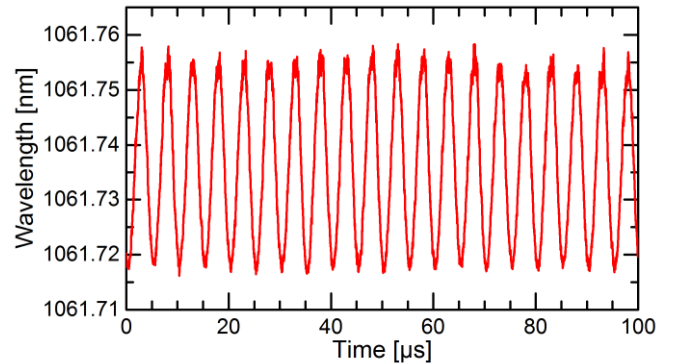


Fig. 5. Test (ii). SHG technique measurement of the wavelength of the laser diode during a 200 kHz modulation of one of the injection currents. The 20 mm crystal was used for this measurement. 200 kHz was the bandwidth limit of the current driver, and the SHG Technique easily resolves it.

In test (ii) the measurement rate of the system was increased by connecting the fast photodiodes to the oscilloscope and calibrating them using the power meters. Fig. 5 shows measurements where the wavelength of the laser diode was modulated by changing an injection current of the laser diode. Fig. 5 also shows that the 200 kHz modulation is clearly resolved with our system. Unfortunately, the

resolution is lower than in Fig. 4 because of the low bit depth of the oscilloscope. Furthermore, the traces taken with the oscilloscope had a significantly higher noise than the power meters. Unfortunately, we are unable to cross check the absolute wavelength with this high measurement rate so we cannot give an estimate of the absolute accuracy for measurements with the photodiodes.

In test (iii) the response time of the technique was investigated by inducing a mode hop in the laser diode with a slow ramp of an injection current. The resulting wavelength measurement is shown in Fig. 6. The measured wavelength jump is 55 pm, which is consistent with the longitudinal mode spacing of the laser diode.

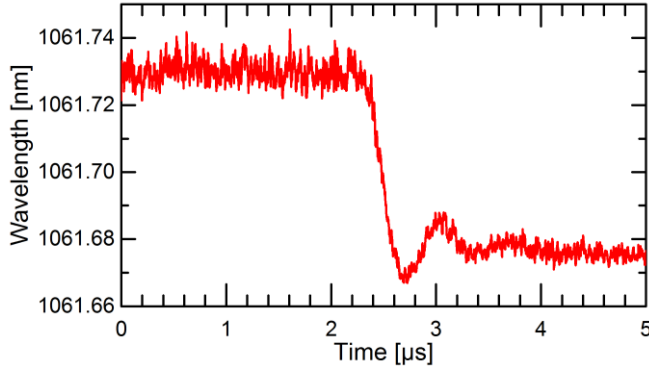


Fig. 6. Test (iii). Step-change response of the SHG technique, shown as the calculated wavelength change over a laser mode hop. The fall time is consistent with the bandwidth of the photodetector.

The fall time of the signal is 0.2 μs (90 to 10%), which is consistent with the specified bandwidth of the photodetector. Since the SHG process itself responds to wavelength changes on optical time scales, the photodiode bandwidth is in practice the limiting factor for the measurement rate of the SHG technique. It can, therefore, be made at least three orders of magnitude higher by using a faster photodiode.

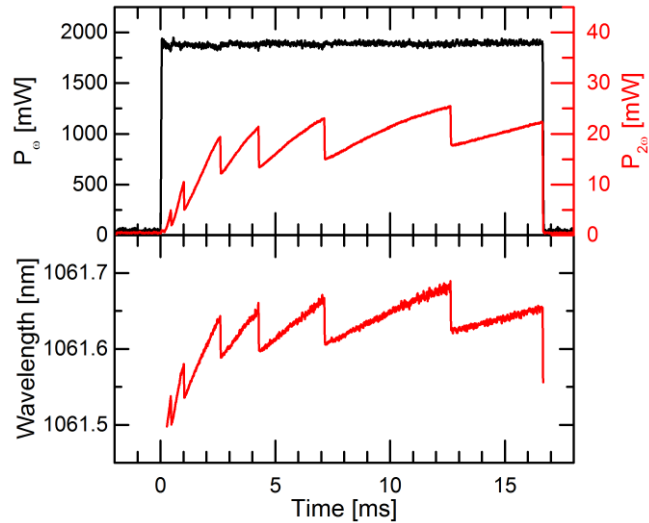


Fig. 7. Test (iv). Behavior of the fundamental power, second harmonic power and wavelength of the laser diode during a single pulse. The high measurement rate clearly resolves the mode hops and the slope of the wavelength change at different times during the pulse.

In test (iv) the system was used to characterize the mode behavior of the laser diode during pulsed operation. A square current pulse was delivered to the laser diode and both the fundamental and second

harmonic powers were measured. The measurement results on a single pulse are shown in Fig. 7. The figure shows that while the infrared power was stable throughout the pulse, the wavelength drifted at least 200 pm and the laser underwent at least 6 mode hops.

3. SUMMARY

To summarize, we have demonstrated a new technique for measuring fast wavelength dynamics of laser diodes based on the wavelength-dependent non-linear SHG efficiency of a non-linear crystal.

We demonstrated a sub-picometer wavelength resolution using both 8 mm and 20 mm long PPLN crystals and a measurement rate in the MHz range using cheap commodity photodetectors. The measurement rate is ultimately limited by the bandwidth of the photodiodes and can, therefore, reach the GHz range to resolve temporal dynamics in the ns range if necessary. The high measurement rate makes the system capable of measuring the wavelength evolution during a single pulse from a diode laser. The main limitation on the resolution for a specific crystal in our setup was the noise on the measurements. Detector noise, stray light and thermal fluctuations of the crystal will limit the system resolution but this can be minimized by enclosing the whole system in a temperature stabilized box. Higher resolution could also be achieved by using longer crystals.

While the narrow operation range on a single crystal means that beforehand knowledge of the approximate wavelength is needed, the high design freedom of quasi phase matched crystals means the system can be designed for any wavelength where crystal material and detectors are available. Furthermore, the calibration of the system is simple and in principle only needs to be performed once for each crystal. The high wavelength selectability of the non-linear crystals means that the measurable wavelength range with each crystal is narrow compared to other techniques. This can to some degree be mitigated by using crystals with multiple periodic poling channels or a fanned out periodic poling structure, but each crystal will still be limited to a range in the order of 100 nm.

The sensitivity of the system is limited by the sensitivity and noise of the detection system. Our setup required a few mW of second harmonic light but with an avalanche photodiode one could use the technique with as little as 10 nW of second harmonic light while still maintaining 10 MHz bandwidth. With the 20 mm crystal this would require roughly 1 mW of fundamental light. We believe this technique can be used to extract a lot of information about fast wavelength dynamics in, e.g., laser diodes, which could be used to find better ways of performing stable on/off modulation of the second harmonic light [7, 8].

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